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Normal incidence infrared photodetectors using intersubband transitions in GaSb L-valley quantum wells have been demonstrated. Enhancement of normal incidence intervalence subband absorption in GaSb quantum wells coupled to a neighboring InAs has been observed. The orientation dependence of infrared absorption in AlAs/AlGaAs x-valley multiple quantum wells grown on GaAs and Si has been studied. InSb films with excellent x-ray rocking curve linewidths have been grown on GaAs and Si by molecular beam epitaxy for infrared detector applications. AlSbAs/InAs heterostructure field-effect transistors with high breakdown voltage has been achieved.

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The research performed under this contract started on July 1, 1991 and ended on June 30, 1994. The emphasis of our research under this program is to obtain high quality III-V arsenides and antimonides materials for infrared and electronic device applications. In the past three years, many device structures and hetero-epitaxial materials based on mixed arsenides and antimonides have been demonstrated. The achievements are summarized in the following:

Normal incidence infrared photodetectors using intersubband transitions in GaSb L-valley quantum wells

We have demonstrated normal incidence infrared detectors based on inter-conduction subband transitions in narrow GaSb/$Ga_{0.6}Al_{0.4}Sb_{0.9}As_{0.1}$ multiquantum wells (MQWs) in which L-valley is the ground state. Strong IR absorption at 7.8 μm with an absorption coefficient of 9100 cm^{-1} and good photodetector response covering a wide spectrum region have been achieved. This is the largest absorption ever reported for this wavelength range. We also studied the orientation dependence of the absorption. Our results indicate the potential of this novel structure for use as normal incidence IR photodetectors.

Quantum well infrared photodetectors (QWIPs) have been attracting a lot of interest recently due to the fact that they can be used to produce large, two-dimensional imaging arrays. Most of the studies on QWIPs have concentrated on the direct-gap material system in which the selection rules forbid inter-conduction subband infrared absorption at normal incidence. Indirect-gap semiconductor quantum well systems can achieve normally incident IR detector structures. For L-valley materials, absorption of normal incidence radiation is allowed for the (100) orientation. We observed normal incidence IR absorption in GaSb (100) and (311) multiquantum wells. An absorption coefficient as large as 9100 cm^{-1} was observed, which represents the largest ever reported for this wavelength range. Good photodetector response covering a wide spectrum region 5-15 μm has also been achieved.

In bulk GaSb the conduction band minimum is at the Γ-point, with the L-valley minimum located only 63 meV above the Γ-minimum. Due to the much smaller effective mass of the Γ valley than that of the L-valleys, the Γ valley can be easily pushed above the L-valley by quantum confinement in narrow GaSb QWs. As a result, for narrow GaSb quantum wells the L-valleys will become the ground state. For the GaSb MQWs designed

in our experiments, the L-valleys become the ground state for a GaSb well thickness of about 5 nm. While the conventional (100)-oriented QWs can be grown with high structural quality, there is an increasing interest in QWs with non-conventional growth directions for the exploration of orientation dependent absorption properties. We have calculated the absorption coefficients for a given sheet doping concentration of 1.5×10^{12} cm^{-2}, and found that absorption coefficients greater than 10^4 cm^{-1} can be easily achieved for normal incident radiation at the wavelength range of 8-20 μm. From our calculation we also found that the absorption of the conventional (100) QWs is smaller than QWs in other growth directions such as (311) and (511).

We performed normal incidence IR absorption measurements at 68K and room temperature, and observed that the (311) sample exhibited a stronger absorption than the (100) sample. The spectra of the (311) GaSb MQWs at 68K have an absorption peaks at 7.8 μm with an absorption coefficient of 9100 cm^{-1}. This is the strongest absorption ever reported in this wavelength range. The spectra of the (100) sample showed a similar absorption peak at 7.4 μm with an absorption coefficient of 8100 cm^{-1}.

We have also grown photodetector structures similar to that used in the absorption experiments. Responsibility peak was observed at 8.3 μm with a photoresponsivity of 310 mA/W. The photocurrent threshold was seen at about 5 μm and the responsivity spectrum covered a wide region of 5-15 μm. Our results indicate the potential of this novel structure for use as normal incidence infrared photodetectors.

Normal incidence intervalence subband absorption in GaSb quantum well enhanced by coupling to InAs conduction band

Quantum well (QW) detectors working in the infrared range (8-14 μm) have attracted a lot of attention in recent years. This is due to their potential ability to make large, two dimensional imaging arrays and various IR sensing devices. Quantum well structures are ideal for these applications because their absorption wavelengths can be gradually adjusted by changing their well widths and barrier heights. Most of the previous studies of these detectors have focused on *n*-type QWs, in which the selection rules forbid intersubband transitions induced by normally incident light. Recently, we proposed and demonstrated normal incidence *p*-type QW detectors which utilize intervalence subband absorption. Due to the inverse relationship between the effective mass of free carriers and the absorption coefficient, QWs with a small effective mass are preferred. Among III-V semiconductors GaSb has the smallest heavy hole effective mass which will lead to a large intervalence subband absorption. We have previously proposed IR detectors based on the

intervalence subband absorption in p-doped GaSb quantum wells. In order to further improve the intervalence subband absorption, we demonstrate in our work a novel IR detector structure based on the type-II InAs/GaSb multiquantum well system. By utilizing the coupling of the valence band states in the GaSb quantum well to the conduction band states in the neighboring InAs, the intervalence subband absorption in the GaSb quantum well is greatly enhanced. We have previously explored this interband coupling mechanism between GaSb and the neighboring InAs for tunneling device applications. Our present experimental results show that a normal incidence IR absorption coefficient as large as 6500 cm^{-1} can be obtained through this novel mechanism in the wavelength range of 8-17 μm. This is the strongest absorption ever observed among all the IR materials in this wavelength range.

In InAs/GaSb multiquantum wells, the Γ band edge lines up in a type-II configuration, i.e. the quantum well for the conduction electrons is in InAs while that for the valence holes is in GaSb. Previous work on InAs/GaSb superlattices indicated that the InAs conduction band edge lies 150 meV lower than the GaSb valence band edge. The intervalence subband transitions from the heavy-hole to light-hole subbands in the GaSb quantum wells are used to absorb the IR signal. The novelty of our structure is that a strong coupling exists between the InAs conduction band and the GaSb valence band: the electrons in InAs couple to the light-hole states of GaSb at the zone center, and they couple to both the heavy-hole and light-hole states away from the zone center due to band mixing. We have previously demonstrated the interband coupling between the electrons in InAs and the holes in GaSb. By using the same mechanism, i.e., when the quantum states associated with electrons in InAs are tuned close in energy to those associated with holes in GaSb, the GaSb valence subband structure is significantly modified due to the induced strong mixing with the InAs conduction band. As a result the optical matrix elements for the heavy-hole to light-hole intervalence subband transitions are tremendously enhanced, which is the mechanism for our observed large absorption.

Molecular beam epitaxial growth of InSb on GaAs and Si for infrared detector applications

InSb p-n junction photodiodes have long been used for infrared detector applications. In addition, due to its high electron mobilty, InSb is an excellent material for high speed electronic and Hall effect device applications. In recent years there also exist a lot of effort in epitaxial growth of materials on foreign substrates such as III-V (including InSb) or II-VI on GaAs and Si in order to take advantage of the mature GaAs and Si device

technology for integration. Such integration, e.g., InSb infrared detectors and GaAs or Si charge-coupled devices, would have significant impact for many applications. Previous reported work established that the nucleation procedure is very important in determining the material properties for InSb on GaAs grown by molecular beam epitaxy (MBE). By using an atomic layer epitaxy buffer layer, material quality of InSb on GaAs was improved. However, there are some drawbacks in the atomic layer epitaxy process: the timing sequence of the shutters needs to be precisely controlled, too many shutter operations are involved, and the growth rate tends to be slow. In our work, we demonstrated an alternative approach using an AlSb intermediate buffer layer. We observed that by using an AlSb buffer layer, excellent InSb epitaxial layers can be easily grown on GaAs and Si. We attribute our results to a very wide MBE growth window for AlSb (substrate temperature in the range of 450^{o}C to 580^{o}C and V/III beam equivalent pressure ratio between 10 and 20) and a reduced lattice-mismatch between AlSb and InSb as compared to that between InSb and GaAs or Si .

We have grown InSb on GaAs and Si substrates by molecular beam epitaxy using an intermediate AlSb buffer layer. The use of an AlSb intermediate buffer layer greatly facilitates the overgrowth of InSb on significantly lattice-mismatched foreign substrates such as GaAs and Si. Hall mobility, X-ray rocking curve, and infrared absorption measurements were performed to charactertize the samples. Using a 300 nm AlSb buffer layer, 3 μm thick InSb films on GaAs and Si substrates with room temperature electron mobilities as high as 55,000 $cm^2v^{-1}s^{-1}$ were routinely achieved. X-ray rocking curve linewidths of 199 arcsec for InSb on GaAs and 230 arcsec for InSb on Si have been achieved, which represent the best results to date. Our results indicate that AlSb is a very effective buffer layer for InSb devices grown on GaAs and Si substrates. This work was reported at the North American MBE Conference and published in J. Vac. Sci. Tech. B11,872 (1993).

Enhancement of intersubband Stark effects in L-valley step quantum wells for infrared modulation and voltage tunable detection

We have proposed a new type of infrared optical modulator employing two-step $Ga_{1-x}Al_xSb/Ga_{1-y}Al_ySb/Ga_{1-z}Al_zSb$ L-valley quantum wells to enhance the Stark shifts of the intersubband transition energy and therefore to achieve large absorption spectral changes with applied bias. Due to the effective-mass anisotropy of electrons in the L-valleys and the tilted growth direction with respect to the valleys, this novel structure can

intrinsically absorb normal incidence light. Under an electric field of 50 kV/cm, a blue shift of the absorption peak from 10.9 to 9.8 μm was found from our calculations in a $Ga_{0.7}Al_{0.3}Sb/Ga_{0.5}Al_{0.5}Sb/Ga_{0.4}Al_{0.6}Sb$ structure. The ability to achieve significant Stark effects with bias makes this structure an attractive choice as vertical infrared light modulators and voltage tunable photodetectors.

Normal incidence infrared absorption in AlAs/AlGaAs X-valley multiquantum wells grown on GaAs and Si substrtates

In order to achieve structures which can intrinsically achieve strong absorption of normally incident light, MQWs consisting of indirect-gap semiconductors are required. Previously, research on indirect-gap (100) QWs has been conducted. The disadvantage of the (100) orientated QW system is that it cannot absorb normally incident light via X-valley electron transitions. We have carried out theoretical analysis of the AlAs/AlGaAs X-valley system. The conduction subband structure was obtained by the transfer matrix method within the effective-mass approximation. The calculation also takes into account a realistic conduction-band offset. We found that the (112) and (113) orientations have stronger normal incidence absorption than QWs with the other growth directions. This is due to the complicated orientation dependence of the reciprocal effective-mass tensor. We have also calculated the absorption coefficient as a function of the general growth direction for the AlAs/AlGaAs X-valley system, and found that normal incidence absorption for (210) and (320) is as strong as that for (112) and (113), as expected on symmetry grounds because the tilting angle for the (113) orientation is similar to that for the (210) and (320) orientation

Experimentally, we demonstrated normal incidence infrared absorption due to inter-conduction subband transitions in AlAs/AlGaAs X-valley multiquantum wells. Infrared absorption measurements were performed on samples grown on (111), (113), (115), and (001) substrates with normal incidence radiation at wavelengths of 5-20 μm. Two absorption peaks were observed in (113) and (115) multiquantum wells with well widths of 4 nm and sheet doping concentrations of 10^{12} cm^{-2}. One peak, due to transitions between the ground state and the continuum band occured at 7.1 μm, a second peak originating from inter-conduction subband transitions between the ground state and the first excited state occured at 17 μm.

To summarize, we have experimentally investigated infrared absorption properties of inter-conduction subband transitions at normal incidence in AlAs/AlGaAs X-valley X-valley MQWs grown in the (113) direction. Substantial absorption coefficients of 2000 cm^{-1} have been measured for normal incidence radiation at the wavelengths of 5-20 μm in

these quantum wells. The peak detectivity D^* can be obtained from $D^*=R_p(A\Delta f)^{1/2}/i_n$, where R_p=0.54A/W and A is the detector' active area. By simple calculation $D^*=5.4*10^{10}$ cm$(H_z)^{1/2}$/W from our detectors operation parameters (g=0.30, $I_D=10^{-6}$A, $i_n=4.3*10^{13}$, at 68K and V_b=1V).

We have also successfully grown the same AlAs/AlGaAs detector structures on Si (113) and (115) substrates. Excellent detector results have been achieved with an absorption coefficient of α=1400 cm^{-1} and quantum efficiency of η=13%. The absorption is due to inter-conduction subband transitions of electrons from the bound state to extended continuum state. The QWIPs on silicon substrates are of special importance since it is convenient to integrate the infrared detectors with Si signal processing circuits on the same wafer.

Infrared absorption in p-type GaSb/GaAlSb quantum wells at normal incidence

Infrared absorption properties at normal incidence in p-type GaSb/$Ga_{1-x}Al_xSb$ quantum wells have been investigated. Normal incidence absorption is intrinsically allowed in conventional p-type quantum wells due to the favorable properties of the p-like valence-band Bloch states and the light-hole and heavy-hole mixing. Unlike s-like conduction-band Bloch states ($|s>$) for electrons, the Bloch states for holes are linear combinations of p-like valence-band Bloch states ($|x>$, $|y>$, and $|z>$), which can provide nonzero coupling to normally incident radiation. The strong heavy-hole and light-hole mixing due to the QW potential further promotes absorption at normal incidence. An advantage of this detection scheme is that it allows the use of wide- and direct-gap semiconductors. However, the inter-valence subband absorption in conventional p-type quantum wells, such as in p-type GaAs/$Ga_{1-x}Al_xAs$, is too small to be useful for photodetection applications. This is because in conventional p-type quantum wells free holes occur primarily in the heavy-hole ground state with large effective masses. Therefore weak absorption results from the inverse relationship between the effective mass of free carriers and the absorption coefficient. Taking into account the fact that smaller effective mass corresponds to stronger absorption, we choose a well material with a relatively small heavy-hole effective mass, GaSb, in order to strengthen the absorption. Among the widely used III-V semiconductors, GaSb has the smallest heavy-hole effective mass (m^*_{hh}/m_0 = *0.26*, m_0 is the free electron mass), which is about half the heavy-hole mass of GaAs (m^*_{hh}/m_0=*0.45*). Previously, we have taken advantage of this feature and

fabricated p-channel GaSb field-effect transistors which exhibited the highest transconductance reported for any III-V compound p-channel field-effect transistors. Here, we found that normal incidence absorption of *3000-6000* cm^{-1} can be easily achieved in these proposed quantum wells with well widths of *55-90 Å* for the wavelength range of *8-12* μm and typical sheet doping concentrations of 10^{12} cm^{-2}. This absorption strength is an order of magnitude larger than that in p-type $GaAs/Ga_{1-x}Al_xAs$ and comparable to that in the intrinsic $Hg_{1-x}Cd_xTe$ detector. Strong absorption of normally incident radiation makes this structure a good candidate for infrared photodetection.

Enhancement of normal incidence infrared absorption in light-hole and heavy-hole inverted strained GaInAs/AlInAs quantum wells

We have studied an alternative approach to improve the inter-valence subband absorption in p-type quantum wells. Absorption at normal incidence is found to be significantly enhanced in $Ga_{1-x}In_xAs/Al_{1-y}In_yAs$ quantum wells with light-hole and heavy-hole inversion. The inversion can be achieved with the effects of biaxial tensile strain in the quantum well due to the lattice mismatch between the well material and substrate. In this way p-type quantum well infrared detectors can be designed such that the light-hole state becomes the ground state for free holes with small effective masses, thereby producing stronger absorption. We found that in this light-hole and heavy-hole inverted structure with a well width of 60 Å, the infrared absorption can be greatly enhanced up to *8500* cm^{-1} for normally incident radiation of *12* μm, which is comparable to that in the intrinsic $Hg_{1-x}Cd_xTe$ detector. This novel structure's ability to detect normally incident radiation makes it promising for infrared photodetection applications.

AlSbAs/InAs Heterostructure Field-Effect Transistors with High Breakdown Voltage

AlSb/GaSb/InAs is a unique combination of materials in that they have very different band gaps yet they are closely lattice-matched. In InAs, the high electron mobility allows carriers to gain velocity quickly, while the large satellite valley spacing should yield higher carrier transient and steady-state velocities than both InP and GaAs. As a result, both long and short channel InAs channel FET's should outperform InP and GaAs based devices. However, because of the narrow bandgap of InAs (0.36 eV) it has been

predicted that breakdown due to impact ionization will severely limit device performance. In bulk InAs, it has been predicted that the threshold for breakdown due to impact ionization should be on the order of 6 kV/cm. To date these results have been supported by the fact that all InAs channel FET's have exhibited behavior indicative of breakdown at drain-to-source voltages near 1 V. In this paper we demonstrated the room temperature operation of an AlSbAs/InAs heterostructure FET (HFET) that operates at channel electric fields (20 kV/cm) several times higher than the predicted threshold for impact ionization. Maximum drain current densities of 450 mA/mm were measured and operation at a drain voltage (V_{ds}) as high as 2.2 V was observed without any indication of channel breakdown. In addition, transconductances as high as 414 mS/mm and output conductances as low as 33 mS/mm are also observed at room temperature, yielding voltages gains on the order of 10. Based upon a calculated source resistance (0.94 W-mm), the intrinsic transconductance was determined to be 670 mS/mm. From this transconductance, the cut-off frequency of the device can be estimated to be 39 GHz which is more than a factor of two greater than is typical for GaAs based FET's of comparable gate length (16 GHz). Also, since carrier velocities are not expected to saturate in InAs, a constant-mobility model is used to project cut-off frequencies in the 600 GHz range for 0.25 μm gate InAs FET's.

In addtion, several mechanisms for the breakdown enhancement have been proposed by us. In general these mechanisms depend on the different vertical and horizontal structure of the FET as compared to a bulk InAs sample. Nonetheless, whatever the reason, our results do demonstrate that bulk breakdown values do not define the limit for operation of InAs channel FET's, establishing that InAs FET's may operate at higher supply voltages than previously considered possible.

AlGaSb/GaSb p-i-n diode with high breakdown voltages and high mobility GaSb grown by molecular beam epitaxy

To date difficulties in the growth and processing of Sb related compounds have limited the progress of AlGaSb-based devices. So far most reported results have been accomplished by liquid phase epitaxy (LPE), however with this technique it is practically impossible to take advantage of bandgap engineered superlattice structures. Therefore, in this project we study the growth of AlGaSb/GaSb PIN diodes by molecular beam epitaxy (MBE). The primary problem with MBE grown AlGaSb/GaSb PIN structures has been the inability to produce sufficiently intrinsic layers that can support the high fields necessary for avalanche operation. While it is well established that high purity MBE grown GaAs is

either very lightly n-type or p-type depending on the residual background impurities, undoped MBE grown GaSb is always p-type, with the p-type conductivity attributed to native defects in GaSb and not residual impurities. The difference between GaSb and GaAs is largely due to the low vapor pressure of Sb compared to As. The vapor pressure of Sb is about five orders of magnitude lower than that of As. As a result, during crystal growth, Sb will tend to aggregate together and form clusters and precipitates. Therefore many Sb lattice sites will be available for other atoms, mainly Ga. This kind of defect, namely Ga antisites (Ga_{Sb}), is a double acceptor since Ga has two less valence electrons than Sb, and explains the fact that undoped GaSb is always p-type. This common problem is also encountered in the growth of GaSb bulk material. It has been demonstrated that the p-type concentration of bulk GaSb decreases as the fraction of Sb in the non-stoichiometric melt is increased and that the primary source of this p-type conductivity is Ga antisite defects. Therefore, to improve the quality of MBE grown GaSb it is necessary to produce a more Sb rich environment.

One means of producing a more Sb rich environment is to perform MBE growth on (111)B oriented substrates. (111) GaSb exhibits an A(Ga) and B(Sb) surface. On the (111) B(Sb) face, the surface is Sb rich with each Sb having three backbonds and one surface dangling bond. In comparison, the (100) face has both Ga and Sb sites with each site having two backbonds. Therefore the (111)B surface has a higher Sb sticking coefficient than the (100) face which yields a larger Sb surface concentration for a given impinging flux value. These features of (111) B face should produce a more Sb rich growth environment reducing the amount of native defects and leading to the growth of more intrinsic layers.

AlGaSb/GaSb PIN diodes were prepared by MBE growth on n^+ GaSb substrates of (100) and (111) B orientations to study this effect. A piece of each orientation was mounted side by side for simultaneous growth of the PIN structure. The structure consisted of a 4 µm unintentionally doped $Al_{0.06}Ga_{0.94}Sb$ layer followed by a 2 µm Be doped p^+ GaSb layer. The substrate temperature during growth was 500 °C. Diodes were defined by standard photolithography and mesas defined by performing a wet chemical etch. The device grown on the (111)B substrate exhibits good diode characteristics while the device grown on the (100) substrate is often quite leaky. The breakdown voltage for the (111)B orientation samples is in the range of 20 V which is the highest demonstrated by MBE growth. The sharp contrast in the characteristics of the devices grown on both orientations clearly shows that the undoped region in the (111)B device is more intrinsic than that of the one grown on the (100) orientation. As noted previously this is attributed to the enhanced Sb incorporation during growth on (111)B substrates.

For this study the (111)B substrates misoriented by 1.5° were utilized, because we have previously shown that slightly misoriented (111)B surfaces yield the best results for the growth of lattice matched materials on (111) oriented GaAs substrates.

To summarize, while MBE grown GaSb is plagued with native defects which make it difficult to obtain uncompensated intrinsic regions, we have demonstrated that growth on the (111) orientation can enhance Sb incorporation thus reducing the p-type conductivity due to native defects. Also, we have demonstrated that the best quality epilayers are achived by growth on slightly misoriented (111)B GaSb substrates. Using slightly misoriented (111)B substrates AlGaSb PIN diodes have been fabricated that exhibit the highest reported breakdown voltage of any MBE grown device.

In addition, since the growth on the (111) orientation is in general much more difficult to perfect than (100) in terms of surface morphology as discussed previously, we propose that the (311)B orientation provides a more optimal growth conditions for GaSb since the (311)B orientation still retains 50% of the (111)B-like Sb-rich character and it also supports a (100)-like monolayer growth mode which is less plagued from defects than (111) growth. To support this claim, growth on (311)B substrates was studied and shown to produce Te-doped GaSb layers with room temperature mobilities of 6780 cm^2/V-s at carrier densities of $9x10^{15}$ cm^{-3} and AlGaSb/GaSb *p-i-n* diode structures with breakdown voltages as high as 20 V. This n-type mobility is an improvement over that reported by Chen and Cho [JAP, 70 , 277 (1991)], 5114 cm^2/V-s at a carrier density of $3.8x10^{16}$ cm^{-3} , and presently represents the highest value achieved for molecular beam epitaxy grown GaSb. Presumably, the high mobilities and high breakdown voltages achieved are due to a reduction of native acceptor-type defects and can be improved in the future through further refinement of the growth process.

PAPERS PUBLISHED IN REFEREED JOURNALS

Zhang, Y., Baruch, N. and Wang, W. I., "AlA/AlGaAs X-valley quantum well normal incidence infrared detectors on Si substrates", J. Appl. Phys. 75, 3690-3692 (1994).

Xie, H., Wang, W.I., and Meyer, J.R., "Infrared electroabsorption modulation at normal incidence in asymmetrically stepped AlSb/InAs/GaSb/AlSb quantum wells", J. Appl. Phys. vol. 75, July 1 (1994)

Hsu, Y., Wang, W.I., and Kuan, T.S., "Molecular beam epitaxial heterostructures in the (311)A orientation", J. Vac. Sci. Tech. B12, 2584-2586 (1994).

Li, L.K., Hsu, Y., and Wang, W.I., "Molecular beam epitaxial growth of InSb on GaAs and Si for infrared detector applications" J. Vac. Sci. Tech. B11, 872-874 (1993).

Katz, J., Zhang, Y., and Wang, W. I., "Normal incidence intervalence subband absorption in GaSb quantum well enhanced by coupling to InAs conduction band", Appl. Phys. Lett., vol. 62, pp 609-611 (1993).

Zhang, Y., Katz, J. and Wang, W. I., "Orientation dependence of normal incidence absorption in ellipsoidal-valley quantum wells", J. Vac. Sci. Tech. vol. B11, pp 1681-1684, (1993).

Xie, H., Wang, W.I., Meyer, J.R., Hoffman, C.A., and Bartoli, F.J., "Enhancement of intersubband Stark effects in L-valley step quantum wells for infrared modulation and voltage tunable detection", J. Appl. Phys., vol 74, pp 1195-1198, (1993).

Xie, H., Wang, W.I., Meyer, J.R., Hoffman, C.A., and Bartoli, F.J., "Normal incidence electroabsorption in GaAlSb/AlSb L-valley quantum wells for 3-5 mm optical modulation", J. Appl. Phys., vol. 74, pp 2810-2812, (1993).

Zhang, Y., Baruch, N. and Wang, W. I., "Nomal incidence infrared photodetectors using intersubband transitions in GaSb L-valley quantum wells", Appl. Phys. Lett., vol 63, pp 1068-1070, (1993).

Xie, X., Zhang, Y., Baruch, N., and Wang, W.I., "Infrared devices based on antimonide quantum wells" (Invited paper), 20th International Symposium on GaAs and Related Compounds, Freiburg, Germany, 1993.

Wang, W.I., "Growth and characteristics of MBE antimonide quantum wells" (Invited paper), MRS Fall meeting, Boston, MA, 1993.

Xie, H., Katz, J., and Wang, W. I., Growth orientation dependence of normal incidence absorption in ellipsoidal-valley quantum wells, App. Phys. Lett., vol. 61, pp 2694-2696, 1992.

Xie, H., Katz, J., and Wang, W. I., Orientation dependence of intersubband absorption in AlAs/AlGaAs x-valley superlattices, J. Appl. Phys. Vol 72, pp 3681-3685, 1992

H. Xie, J. Katz, W.I. Wang, and Y.C. Chang, "Normal incidence infrared photoabsorption in p-type GaSb/GaAlSb quantum wells", J. Appl. Phys. 71, 2844-2847 (1992).

J. Katz, Y. Zhang, and W.I. Wang, "Normal incidence infrared absorption from intersubband transitions in p-type GaInAs/AlInAs quantum wells", Electron. Lett. 28, 932-934 (1992).

Katz, J., Zhang, Y., and Wang, W. I., Normal incidence infrared absorption in AlAs/AlGaAs x-valley multiquantum wells, Appl. Phys. Lett., Vol 61, pp 1697-1699, 1992

X. Li, K.F. Longenbach, Y. Wang, and W.I. Wang, "High breakdown voltage AlSbAs/InAs n-channel field effect transistors", IEEE Electron Dev. Lett. 192-194 (1992).

K.F. Longenbach and W.I. Wang, "AlGaSb/GaSb diodes grown by molecular beam epitaxy", Appl. Phys. Lett. 59, 1117-1119 (1991).

K.F. Longenbach and W.I. Wang, "Molecular beam epitaxy of GaSb" Appl. Phys. Lett. 59, 2427-2429 (1991).

H. Xie, J. Katz, and W.I. Wang, "Infrared absorption enhancement in light-hole and heavy-hole inverted InGaAs/InAlAs quantum wells", Appl. Phys. Lett. 59, 3601-3603 (1991).

H. Xie, J. Piao, J. Katz, and W.I. Wang, "Intersubband absorption in GaAlSb/AlSb superlattices for infrared detection", J. Appl. Phys. 70, 8152-8156 (1991).

INVITED PRESENTATIONS

W.I. Wang, "Molecular beam epitaxial antimonide quantum wells for infrared and high speed device applications", Fall Meeting of the Materials Research Society, December 9, 1994, Boston, MA.

W.I. Wang, "L-valley GaSb quantum wells for IR detector applications", University of Texas Workshop on III-V Antimonide Compounds, March 1, 1994, Austin, TX.

W.I. Wang was a Member of Conference Committee, 21st Conference on Physics and Chemistry of Semiconductor Interfaces, Mohonk, New York, Jan 24-28, 1994.

PROFESSIONAL HONORS

W.I. Wang was elected IEEE Fellow for "contributions to compound semiconductor devices through innovative crystal growth"

PATENTS FILED none

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